Final Technical Report

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Estimating Geologic Slip Rates on the southern San Andreas Fault, California: U-series and ^{10}Be Dating

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Abstract

The potential for a large-magnitude earthquake (Mw ≥ 6.7) on the southern San Andreas fault zone is generally considered high [Working Group on California Earthquake Probabilities, 2007]. However, the proportion of deformation accommodated by each of its three major fault strands (Mission Creek, Banning, and Garnet Hill, from north to south) at the latitude of the Indio Hills, and hence the seismic risk associated with each fault strand, is poorly constrained. To better assess the relative importance of two of these faults and their potential for a major earthquake, we determined late Pleistocene-Holocene horizontal fault-slip rates on the Mission Creek and Banning faults in the central Indio Hills by dating landforms offset along the two faults. We have also constrained rates of vertical fault-slip and related deformation on the Banning strand by dating a fan with measurable vertical offsets, estimating erosion rates using ^{10}Be concentrations in alluvial sands, and estimating Quaternary sediment volumes eroded from the Indio Hills using stratigraphic relations and a 10-m DEM enveloping surface. Previous work on the Mission Creek fault strand in the southern Indio Hills at Biskra Palms, demonstrated a horizontal slip rate of between 12 and 22 mm/yr, with a preferred rate of 14-17 mm/y (Behr et al., 2010). From the southern Indio Hills it has been generally assumed that the horizontal slip rate on the Mission Creek fault strand decreases northwestwards, as slip is transferred via horizontal and vertical motion along the Banning fault strand in the central Indio Hills. However, uranium-series dating of pedogenic carbonate and ^{10}Be cosmogenic exposure dating of surface clasts from four offset landforms with ages of about 90, 70, 25, and 2.5 ka indicate that slip on the Mission Creek fault strand in the central Indio Hills has occurred at a relatively constant, and unexpectedly fast, horizontal slip rate of ~22-25 mm/yr. In contrast, an alluvial fan offset along the Banning fault strand near Thousand Palms Oasis indicates a relatively slow slip rate of <1.5 mm/yr during the late Pleistocene. Estimates of long- and short-term vertical slip rates along the Banning fault strand overlap within their respective uncertainties and indicate minimum uplift rates of ~0.08 to 0.34 mm/yr, with uplift rates increasing westward along the restraining bend of the southern San Andreas fault zone.

Objectives

The goals of our investigation of the southern San Andreas fault zone in the Coachella Valley were threefold: 1) to provide information needed to refine earthquake hazard models for the Coachella Valley and adjacent regions by developing improved estimates of late Pleistocene-Holocene fault slip rates on the southern San Andreas fault zone near its bifurcation into the Mission Creek and Banning strands (Figure 1); 2) to develop and apply U-series dating of pedogenic carbonate using laser ablation ICP-MS and assess whether the enhanced spatial resolution of the technique yields more accurate dates for offset landforms; and, 3) to provide observations essential to developing first-order mechanical models of fault behavior for the San Andreas fault system.

Results

Funding from USGS award no. G13AP00032 provided support for more than 60 U-series ages of pedogenic carbonate determined at the Berkeley Geochronology Center and 25 ^{10}Be analyses including 19 cosmogenic nuclide surface exposure ages and six erosion rate determinations. The U-series and ^{10}Be dates provide ages for landforms measurably offset along the Mission Creek and Banning strands of the San Andreas fault, allowing us to determine geological fault-slip rates. Analyses of ^{10}Be concentrations of six fluvial sands from catchments in the Indio Hills allow us to estimate erosion rates, which are to a first order controlled by vertical deformation rates. We have used these data to determine new horizontal and vertical fault slip rates at locations along the Mission Creek and Banning fault strands over the past ~2.5 ka, ~20-40 ka, ~60 ka, ~70 ka and ~100 ka.

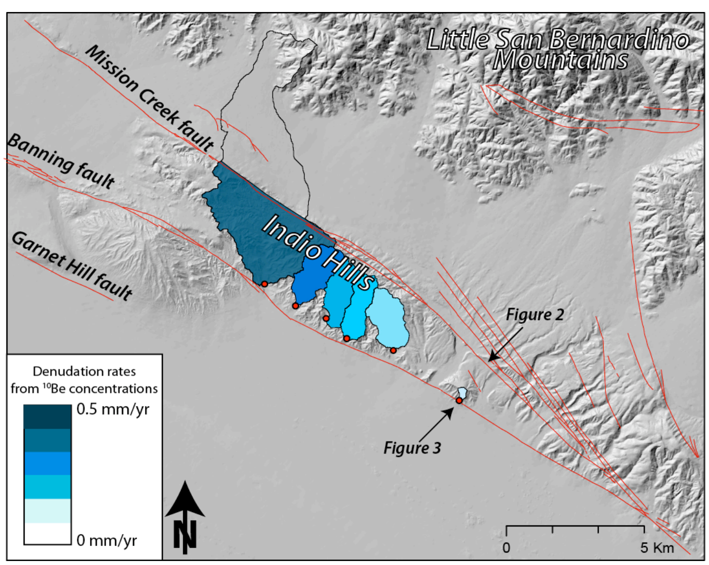

Figure 1. Map of study area showing the location of the Mission Creek, Banning, and Garnet Hill fault strands of the southern San Andreas fault system. The highlighted polygons show the location of catchments along the Indio Hills where denudation rates have been determined from ^{10}Be concentrations to determine uplift rates along the Banning fault strand.

Our geochronologic investigations along the Banning and Mission Creek fault strands, in combination with field and LiDAR studies by PI Blisniuk and Dr. Katherine Scharer (USGS), have fundamentally challenged our current understanding of the relative roles of these two active structures in accommodating slip on the southern San Andreas Fault system. We have found an unexpectedly fast horizontal slip rate of 19-24 mm/yr on the Mission Creek fault strand at Pushawalla Canyon over all time intervals measured in the last ~100 ka, and an unexpectedly slow horizontal slip rate of 0.4-1.5 mm/yr since the late Pleistocene on the Banning fault strand in the central Indio Hills. (See Figures 2 and 3 for summary of ages and offsets). The new slip rates will be incorporated into the Earthquake Hazards Program at the USGS and UCERF3 (http://pubs.usgs.gov/of/2013/1165/), the two main sources of seismic hazard assessment in the United States.

Our new results suggest an alternative kinematic model for the southern SAFZ in which *a San Andreas fault zone earthquake may rupture on the Mission Creek fault strand and continue northward on a narrow structure through the San Gorgonio Pass, instead of following the Banning fault strand*. While additional work is needed to better understand how slip along the SAFZ is partitioned in the northwestern Indio Hills, our new findings underscore the seismic hazard posed by the Mission Creek fault strand in this region. For example, our new data may be combined with published paleoseismic studies for the Mission Creek fault strand (Fumal, 2004), which show an average earthquake recurrence interval of 225 years for the past 5 events since 900 AD. Since the last earthquake to rupture this section of the Mission Creek fault occurred over 300 years ago (ca. 1690), our new slip rates indicate that ca. 6.0 to 7.5 m of strain has accumulated since last event and could be released in the next earthquake.

Slip rate sites and dates

In the following paragraphs we summarize our results. Slip rate sites are located in the Indio Hills near Thousand Palms (Figures 2 and 3).

<u>*Site 1: Pushawalla Canyon, Mission Creek fault strand*</u>

Site 1 is located in the central Indio Hills where three paleo-channels (C1, C2, and C3) are offset from their source in Pushawalla Canyon by the Mission Creek fault strand (Figure 2). These channels are incised into older alluvial fans and filled by younger sediment deposited by the stream issuing from Pushawalla Canyon. Fluvial terrace deposits are also preserved to the northeast of the fault in Pushawalla Canyon. These terrace deposits correlate with the distinct sediment fills within the abandoned channels (see Figure 2, C1, C2, and C3) and therefore provide an excellent suite of offset geomorphic markers along the Mission Creek fault strand spanning three distinct time intervals (Figure 2). Re-alignment of the three paleo-

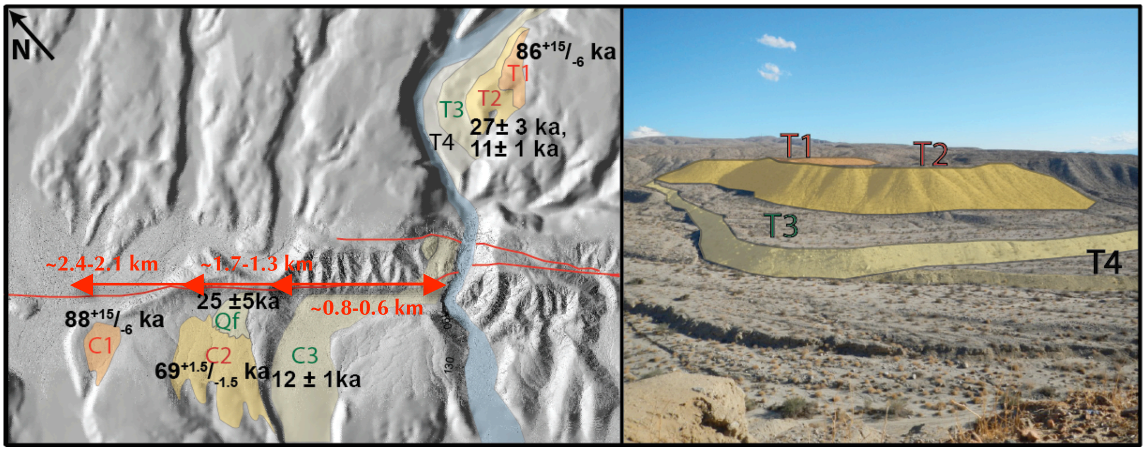

Figure 2. Slip rate site 1, Pushawalla Canyon in the central Indio Hills. See Figure 1 for location. Left panel, present-day image of beheaded channels (C1, C2, C3) offset along the Mission Creek fault strand (red line). Correlative terraces (T1, T2, and T3) are shown in Pushawalla Canyon. Red arrows show measured offsets, black numerals are ages based on ^{10}Be exposure dating and U-series dating of pedogenic carbonate. Right panel, field photo of inset terraces T1 through T4 in Pushawalla Canyon.

channels to Pushawalla Canyon indicate that C1 and C2 are dextrally offset by, respectively, ~2.4 to 2.1 and ~1.7 to 1.3 km. A minimum offset of ~600-800 m is estimated for the incision of the northwesterly wall of C3 (Figure 2).

To determine the slip rates on the Mission Creek fault strand recorded by the three beheaded channels, we dated the abandoned river terraces (T1, T2, T3, and T4) in Pushawalla Canyon and the alluvium in channels C1, C2, and C3 and a fan deposit (Qf) in C2 (Figure 2). Dating of the alluvium with ^{10}Be surface exposure dating and U- series dating of pedogenic carbonate in the abandoned channels and the flight of fluvial terraces indicate C1 and T1 were abandoned ~90 ka, C2 and T2 were abandoned ~70 ka, and C3 and T3 were abandoned ~12 ka. Dating the alluvial fan in C2 yielded an age of ~25 ka and provides a maximum incision age for the northwest wall of C3. Combining these ages with our estimated offsets indicate mean fault-slip rates of 21-29 mm/yr since ~90 ka, 19-25 mm/yr since ~70 ka, and 21-35 mm/yr since ~25 ka. These slip rate estimates overlap within their respective uncertainties and suggest a rate of ~22-25 mm/yr for the Mission Creek fault strand in the Central Indio Hills for the past 90 ka. Similar slip rates are indicated by an offset debris cone with a preliminary age assignment of ~ 1.2 ka, which is located ~4 km to the southeast along the Mission Creek fault; however, more ages from this deposit are needed to constrain the slip rate at this location. These pending results will be incorporate into our present results to better understand Holocene deformation across this region.

Site 2: Thousand Palms Oasis, Banning fault strand

Site 2 is located ~1km to the southwest of Site 1 on the sub-parallel Banning fault strand near Thousand Palms Oasis in the Central Indio Hills (Figure 1), where an alluvial fan is offset vertically (~2 m) and horizontally (>3 to as much as 30 m) by multiple splays of the Banning fault strand. To constrain the maximum horizontal offset of ~30 m at this site we re-aligned the depositional contact between the alluvial fan and bedrock (Figure 3). The minimum offset of 3 m re-aligns bar-and-swale surface topography of the alluvial fan. Initial U-series ages of pedogenic carbonate suggest a minimum soil age of ~60 ka. However the ^{10}Be exposure age suggest the surface became stable ~18 ka. Combining the age range provided by the U-series and ^{10}Be ages for the fan with the minimum and maximum possible offsets observed yields horizontal and vertical slip rates of, respectively, 0.1- 1.5 mm/yr and 0.03-0.1 mm/yr, respectively for the Banning fault strand in the Central Indio Hills.

To better constrain the vertical slip rate on the Banning fault strand in the Central and Northern Indio Hills, we also estimated uplift rates along the Central Indio Hills. New long- and short-term erosion rates across the Indio Hills indicate vertical rates of 0.1 to 0.4 mm/yr. Two methods were applied to estimate uplift rates. Long-term rates are calculated from eroded volumes estimated from a 10-m DEM surface enveloping the Indio Hills assuming that all folding and uplift initiated ca. 500 ka (the 750 ka Bishop ash is uplifted and warped within the Indio Hills). Short-term rates are determined from ^{10}Be concentrations of alluvial sand eroding from the Indio Hills. Short-term rates from 6 catchments along the Banning fault strand show a gradual increase to the northwest in the Indio Hills from 0.08 mm/yr to 0.34 mm/yr (Figure 1). Similar long- and short-term rates suggest steady state uplift during the late Pleistocene to Holocene.

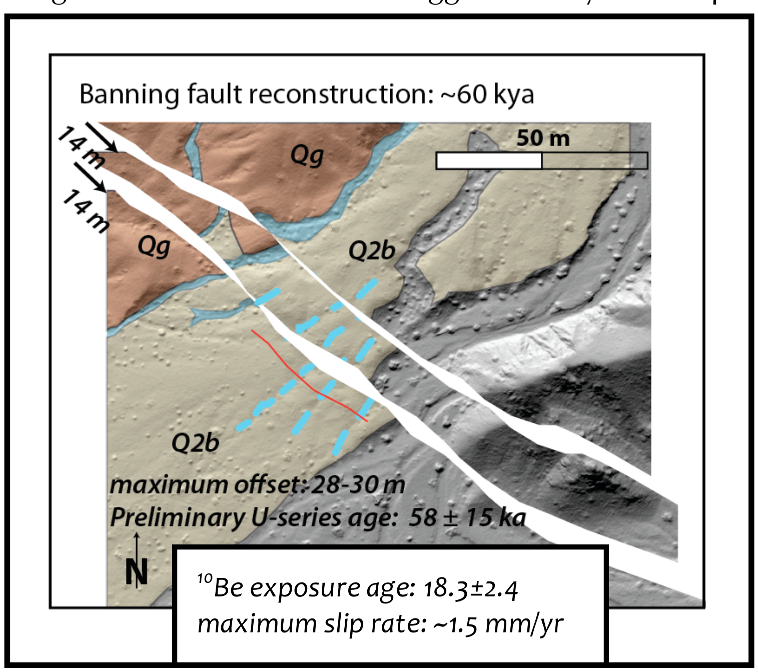

Figure 3. Slip rate site 2, Thousand Palms Oasis, showing maximum offset reconstruction of the Banning fault strand along one splay of the fault. The reconstruction re-aligns the incised contact of the alluvial fan with bedrock.

Laser ablation U-series dating of pedogenic carbonate

We have developed U-series dating of pedogenic carbonate via LA-ICP-MS and applied it to samples from the Pushawalla Canyon site. While U-series and ^{10}Be dates at this site for alluvium ~70 ka or younger generally show reasonable agreement, U-series dates for the oldest channel (channel C1) do not exceed 64.7±2.1 ka and are systematically younger than ^{10}Be dates of up to 82.3±7.6 ka from the same deposit. This discrepancy could be due to inadequate correction for inherited ^{10}Be, making the cosmogenic dates too old, or to accumulation of pedogenic carbonate clast-coatings over a prolonged period (thousands of years) after alluvial deposition, causing U-series ages to underestimate the depositional age when the entire thickness of the coating (ca. 0.5 mm) is dated via conventional sampling followed by solution ICP-MS analyses.

Using laser ablation U-series analyses of cut and polished slabs of laminated carbonate clast-coatings, we can date relatively thin intervals (100 μm) of the coating, allowing us to resolve age gradients, if any are present. For example, Figure 4 shows the tracks of three parallel line scans, each 100 μm wide, along growth bands of pedogenic carbonate coating an alluvial clast from Pushawalla channel C1. Each track gives us a date for a thin layer of the coating. During analysis, the sample is moved slowly under a UV laser beam pulsing five times per second while the resulting aerosol is aspirated into an ICP-MS and analyzed for ^{235}U, ^{234}U, ^{232}Th, and ^{230}Th. Corrections for mass bias and the relative sensitivities of U and Th are made by analyzing a carbonate standard of known age several times during a session. Corrections are also made for instrumental blanks, the tailing of large peaks (e.g., ^{232}Th) onto small peaks (^{230}Th), and initial ^{230}Th from impurities silicate detritus. Outward from the clast, ages for the four scans (the fourth, outermost scan is not shown in Figure 4) are 68.9±4.4, 76.4±5.0, 73.0±4.7, and 57.8±3.5 ka indicating that the coating had a prolonged history of growth. The age of the oldest part of the coating, ~75 ka, provides support for an age of >75 ka for offset channel C1, more closely approaching the ^{10}Be dates from that channel.

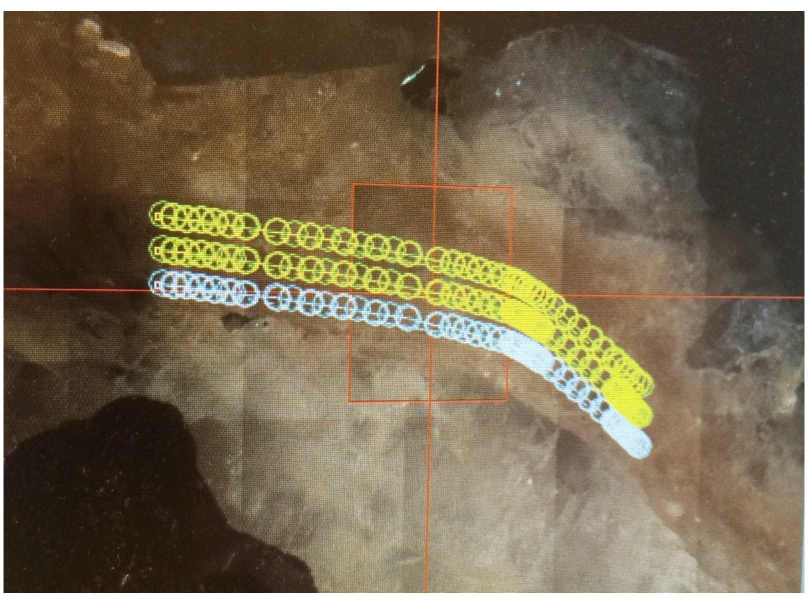

Figure 4. Cut and polished slab of quartzo-feldspathic pebble from channel C1 with tan pedogenic carbonate coating (inverted from field position). Three tracks scanned for laser ablation U-series dating are shown. Circles are 100 um in diameter. A fourth track, parallel to the first three and farther from the clast, is not shown.

Implications for the San Andreas fault system

In contrast with the study of Fumal et al. (2002), which indicated a low slip rate for the Mission Creek fault in the southern Indio Hills (4±2 mm/yr), our new slip rates for the Mission Creek and Banning strands in the southern Indio Hills indicate that the Mission Creek strand continues to carry most of the slip accommodated on the southern San Andreas fault at least as far north as our study area; that is, well north of the mapped bifurcation of the Banning and Mission Creek strands. Further work is needed to determine if such high slip rates persist on the Mission Creek northward into the vicinity of San Gorgonio Pass.

Our new results complement slip rates recently determined for the adjacent, sub-parallel San Jacinto and Elsinore fault zones [Blisniuk et al., 2010; Fletcher et al., 2011; Blisniuk et al., 2013]. They allow an integrated assessment of slip rates across these three fault zones that account for approximately 70-90% of the relative motion along the Pacific-North American plate boundary at this latitude and hence are the sources of much of the seismic hazard in southern California. A steady slip rate on the Mission Creek strand of ~22-25 mm/yr for the past ~90 ka is not consistent with mechanical and kinematic models in which the sub-parallel San Jacinto fault currently acts as the dominant structure across the Pacific-North American plate boundary, nor with models in which the fastest slip rate has alternated between the San Andreas and San Jacinto fault zones over the past 100 ka [e.g., Bennett et al, 2004]. In contrast, our new results support kinematic and mechanical models for the San Andreas fault system dominated by slip on the San Andreas fault *sensu stricto*.

References Cited

Behr, W., D. Rood, and K. Fletcher, N. Guzman, R. Finkel, T.C. Hanks, K.W. Hudnut, K.J. Kendrick, J.P. Platt, W.D. Sharp, R.J. Weldon and J.D. Yule (2010), Uncertainties in slip-rate estimates for the Mission Creek strand of the southern San Andreas fault at Biskra Palms Oasis, southern California. Geological Society of America Bulletin 122: (9-10), 1360-1377.

Bennett, R., W. Rodi, and R. Reilinger (1996), Global Positioning System constraints on fault slip rates in southern California and northern Baja. Journal of Geophysical Research-Solid Earth, 101: 21,943-921,960.10.1029/96JB02488.

Blisniuk, K., Oskin, M.E., Anne-Sophie Meriaux, Rockwell, T., Finkel, R., and Ryerson, R., (2013) Stable, rapid rate of slip since inception of the San Jacinto fault, California. Geophysical Research Letters 40: (16) 4209-4213.

Blisniuk, K., Rockwell, T., Owen L.A., Oskin, M., Lippincott, C., Caffee, M.W., and Dortch, J., (2010), Late Quaternary slip rate gradient defined using high-resolution topography and ^{10}Be dating of offset landforms on the southern San Jacinto Fault zone, California. Journal of Geophysical Research. 115: B08401, doi:10.1029/2009JB006346.

Fletcher, K.E., Sharp, W.D., Kendrick, K.J., Behr, W.M., Hudnut, K.W., and Hanks, T.C., (2010). $^{230}Th/U$ dating of a late Pleistocene alluvial fan along the southern San Andreas fault. Geological Society of America Bulletin 122: (9-10), 1347-1359.

Fumal, T., M. Rymer, and G. Seitz (2002), Timing of large earthquakes since AD 800 on the Mission Creek strand of the San Andreas fault zone at Thousand Palms Oasis, near Palm Springs, California. Bulletin of the Seismological Society of America 7: 2841-2860, 10.1785/0120000609

van der Woerd, J., Y. Klinger, K. Sieh. P. Tapponnier, F. J. Ryerson, and A. Meriaux (2006), Long-term slip rate of the southern San Andreas Fault from ^{10}Be-^{26}Al surface exposure dating of an offset alluvial fan. Journal of Geophysical Research-Solid Earth 111: B04407.10.1029/2004JB003559.

Bibliography

There are no publications resulting from work performed under this award as of the current date.